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Mechanical loading of the low back and shoulders during pushing and pulling activities

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The objective of this study was to quantify the mechanical load on the low back and shoulders during pushing and pulling in combination with three task constraints: the use of one or two hands, three cart weights, and two handle heights. The second objective was to explore the relation between the initial and sustained exerted forces and the mechanical load on the low back and shoulders. Detailed biomechanical models of the low back and shoulder joint were used to estimate mechanical loading. Using generalized estimating equations (GEE) the effects were quantified for exerted push/pull forces, net moments at the low back and shoulders, compressive and shear forces at the low back, and compressive forces at the glenohumeral joint. The results of this study appeared to be useful to estimate ergonomics consequences of interventions in the working constraints during pushing and pulling. Cart weight as well as handle height had a considerable effect on the mechanical load and it is recommended to maintain low cart weights and to push or pull at shoulder height. Initial and sustained exerted forces were not highly correlated with the mechanical load at the low back and shoulders within the studied range of the exerted forces.

1. Introduction

Physical work load and more specifically manual materials handling is generally considered to be an occupational risk factor for low back and shoulder complaints (Bernard 1997, Hoogendoorn *et al*. 1999, Kuiper *et al*. 1999, Van der Windt *et al*. 2000). Pushing and pulling have not been the primary subject of epidemiological studies, but several studies reported that 9–20% of the injury claims for low back

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pain were associated with pushing and pulling (Hoozemans *et al.* 1998). Furthermore, in a study among lorry drivers Van der Beek *et al.* (1993) found a significantly increased risk for shoulder pain when subjects regularly pushed or pulled wheeled cages. Although epidemiological studies provide important indications as to the causality of the association, laboratory studies and biomechanical models may provide complementary information needed to understand the process of how exposure to pushing and pulling ultimately may lead to low back or shoulder complaints (Keyserling 2000a,b).

Potential risk factors of pushing and pulling in relation to low back and shoulder complaints are, amongst others, the direction of the exerted forces (pushing or pulling), one or two handed pushing or pulling, cart weight, and handle height (Hoozemans *et al.* 1998). The effect of these risk factors on the physical work load has mainly been studied at the level of exerted hand forces and net moments at the low back and shoulders (e.g., Van der Woude *et al.* 1995, De Looze *et al.* 2000a). The net moment is the resultant of all moments around the joint caused by different anatomical structures and thus gives no information about the mechanical stress at these specific structures, e.g., compressive forces at the intervertebral discs. Compressive and shear forces at the low back have mainly been estimated using single equivalent muscle models (SEM, e.g., Lee *et al.* 1991). However, it is assumed that for pushing and pulling the validity of such models is low (Andres and Chaffin 1991, Lee *et al.* 1989). To the authors' knowledge, the loading of the shoulder region during pushing and pulling in terms of mechanical stress at anatomical structures, e.g., compressive forces at the glenohumeral joint, has never been explored. The application of detailed biomechanical models of the low back and shoulder may reveal new insights with respect to mechanical stress at anatomical structures. Therefore, the main objective of the present study was to quantify the effect of pushing and pulling in combination with three task constraints: the use of one or two hands, cart weight, and handle height. The effects were quantified for exerted push/pull forces, net moments at the low back and shoulders, compressive and shear forces at the low back, and compressive forces at the glenohumeral joint using detailed biomechanical models.

Risk evaluation of pushing and pulling during work situations is generally aimed at the assessment of initial exerted forces, required to accelerate the object, and sustained exerted forces to keep the object at a more or less constant velocity (Snook 1978). The initial and sustained forces are usually compared to psychophysically determined maximum acceptable forces corresponding to the actual work situation (Snook and Ciriello 1991, Mital *et al.* 1997). The rationale behind the concept of psychophysically determined maximum acceptable forces is that exceeding these values will increase the risk of developing musculoskeletal complaints. As it is generally considered that an increase in risk may be caused by an increase in mechanical loading, the question arises whether exerted push or pull forces are related to mechanical loading in terms of net moments and compressive forces. Therefore, the second objective of the present study was to examine the relation between exerted push and pull forces and mechanical loading at the low back and shoulders at the initial and sustained phases of pushing and pulling. The hypothesis was that higher exerted initial and sustained forces are related to higher mechanical loading, as derived from biomechanical modelling.

2. Methods

2.1. *Participants*

Seven healthy male workers, age 33.7 years (SD 6.2), stature 1.78 m (SD 0.12), body mass 76.2 kg (SD 18.1), participated in the experiments. They all performed pushing and pulling tasks on a daily basis during their work. All participants gave informed consent prior to the experiments and reported no history of low back pain or other musculoskeletal problems.

2.2. *Tasks and procedures*

Preliminary field studies using on-site observations provided information on frequent pushing and pulling activities in pre-selected physically demanding professions. The most frequent pushing and pulling activities were simulated in the laboratory. A standard four-wheeled cart (height 1.6 m, depth 0.8 m, width 0.64 m), as used in postal distribution centres, was used in the experiments. The cart is described in more detail in Van der Beek *et al*. (2000). The cart had hard rubber wheels, which were 0.032 m width and had a diameter of 0.12 m. Participants had to perform pushing and pulling activities with different combinations of task constraints: using one or two hands, three cart weights, and two handle heights. The participants were instructed to push or pull the cart symmetrically with both hands or using the right hand only. According to the actual loading of such carts in the field, the total weight of the cart varied between 85, 135 and 320 kg. Handle height was individually adjusted at hip height (mean of participants: 0.91 m (SD 0.05)), or at shoulder height, (mean of participants 1.46 m (SD 0.10)). For each trial, the participants had to displace the cart over a distance of 4 m, from and until standstill. Furthermore, the participants had to start each trial while the castor wheels of the cart were under a 90° angle to the direction of the movement. The pushing and pulling activities were performed on a level hard rubber surface. Rolling resistance of the cart was comparable to moving the cart on an asphalt surface (Al-Eisawi *et al*. 1999).

The participants performed a few practice trials before the actual measurements started. The different trials were presented in random order. The imposed trials were based on the information of the on-site observations at the work place and only the most frequent pushing and pulling activities were selected for simulation. Because the biomechanical analyses were part of the (internal) exposure assessment for an epidemiological study, it was decided not to study infrequent activities. Table 1 presents the combinations that were assessed in the experiments. Pulling a 135 kg cart with one hand, pushing a 320 kg cart with one hand, and pulling a 135 kg cart with two hands at shoulder height were not assessed in the experiments because these activities appeared to be very rare at the work place.

2.3. *Exerted forces and kinematics*

Two 3D force transducers (SRMC3A series, Advanced Mechanical Technology, Inc., USA) were attached to the cart to assess the exerted forces. LED markers were attached to the left and right side of the body at the level of the L5-S1 joint. Furthermore, markers were attached at the shoulders, the right side of the thorax, the elbows, the right wrist, and the cart. The 3D marker positions were recorded using an opto-electronic system (Optotrac, Northern Digital Inc., Canada). Exerted forces and marker positions were sampled at 50 Hz.

Table 1. Measurement scheme (x = condition that is measured).

		Cart weight 85 kg		Cart weight 135 kg		Cart weight 320 kg	
		Hip height	Shoulder height	Hip height	Shoulder height	Hip height	Shoulder height
Pulling	One hand	x	x			x	x
	Two hands	x	x	x		x	x
Pushing	One hand	x	x	x	x		
	Two hands	x	x	x	x	x	x

2.4. *Biomechanical model of the low back*

Kinematics and anthropometrical data were used as input for an upper body quasi-dynamic 3D linked segment model (Kingma *et al.* 1996). The linked segment model consisted of five segments: left and right forearms plus hands, left and right upper arms, and trunk plus head. Net moments at the L5-S1 level were calculated using standard linked segment mechanics.

During the experimental pushing and pulling activities, surface-EMG recordings were made of eight bilateral muscle pairs of the trunk according to Van Dieën and Kingma (1999) using bipolar disposable Ag-AgCl electrodes. Signals were amplified 20 times, band-pass pre-filtered (10 – 400 Hz) and A – D converted (22 bits at 1600 Hz). All signals were high-pass filtered (FIR) at 30 Hz to reduce cardio-electric interference (Redfern *et al.* 1993), and subsequently low-pass filtered (Butterworth) at 2.5 Hz after full-wave rectification. Filtered data were normalized to the maximum value found in maximum voluntary contraction tests derived from McGill (1991).

An EMG driven distribution model was used to estimate compressive and shear forces at the L5-S1 intervertebral disc. The model has in part been described previously (Van Dieën 1997, Van Dieën and Kingma 1999). Muscle forces were estimated as the product of maximum muscle stress, normalized EMG amplitude, and correction factors for instantaneous muscle length and contraction velocity plus the passive force developed by the muscle's connective tissue. Maximum muscle stress was iteratively adjusted to obtain maximum agreement between the time series of muscle moments and net external moments (cf. McGill and Norman 1986). The anthropometry of the model was scaled to the anthropometry of the participants. Compressive and shear forces were determined by the sum of the forces of the muscle slips as defined by the model, the gravitational forces resulting from the mass of the upper body, and the cart reaction forces at the hands. Shear forces are considered positive when the 5th lumbar vertebra moves posterior with regard to the position of the sacrum.

2.5. *Biomechanical model of the shoulder*

The mechanical loading of the shoulder was estimated using a dynamic 3D model (Van der Helm 1991). The model is based on the finite element theory (Van der Helm 1994) and has been validated in several studies (Van der Helm 1991, Happee and Van der Helm 1995, De Groot 1998). Standardized postures of the participants were assessed prior to the experiments to record the position of bony landmarks in relation to LED marker positions (Van der Helm and Veeger 1996). During the experiments, the LED marker positions at the thorax and upper arm were used to predict the position of the scapula, the clavicula, and the glenohumeral joint rotation centre (Meskers *et al*. 1998). The anthropometry of the participants was scaled to the anthropometry of the model (Veeger *et al*. 1991). The kinematics and the exerted forces at the right hand were used to calculate moment and force components around three axes through the right glenohumeral joint.

2.6. *Statistical analyses*

Three dimensional exerted force and net moment components were used to calculate resultant exerted forces and resultant net moments at the low back and shoulder joint. The maximum exerted force, maximum net moment at the low back and shoulder, and maximum compressive and shear force at the low back were determined for each trial. Due to the dynamical properties of the pushing and pulling activities and a too frequent loss of marker information, it appeared not to be possible to estimate compressive forces at the genohumeral joint during the entire trial. Thus, the maximum compressive force at the glenohumeral joint could not be determined. Initial exerted forces were defined as the maximum in the period from the beginning of the trial to the instant that the cart reached 80% of its maximum velocity. At the instant of the initial exerted force, the net moment at the low back and shoulders were calculated as well as the compressive and shear forces at the low back and the compressive forces at the glenohumeral joint. The sustained phase was defined as the time period of 2 s during which the velocity of the cart was higher than the mean velocity of the cart while at the same time the period contained the lowest mean acceleration of all 2 s periods that fit within the time that the velocity was higher than the mean velocity. The sustained phase was determined for each trial. Mean values during the sustained phase were determined for the resultant exerted force, the resultant net moment at the low back and shoulder, the compressive and shear forces at the low back, and the compressive forces at the shoulder joint.

The effect of pushing or pulling, the use of one or two hands, cart weight, and handle height on all measures of the exerted forces, net moments, and compressive and shear forces was quantified using generalized estimating equations (GEE) (Liang and Zeger 1993). The analyses consider the measurements within participants as repeated measurement and account for this dependency. In the GEE analysis the factors of interest were coded according to:

$$\text{outcome} = \text{constant} + \text{B1} \cdot \begin{pmatrix} \text{pushing} = 0 \\ \text{pulling} = 1 \end{pmatrix} + \text{B2} \cdot \begin{pmatrix} \text{two handed} = 0 \\ \text{one handed} = 1 \end{pmatrix} + \\ \text{B3} \cdot \text{cart weight (kg)} + \text{B4} \cdot \begin{pmatrix} \text{hip height} = 0 \\ \text{shoulder height} = 1 \end{pmatrix}$$

where B1 – B4 are regression coefficients and the constant comprises the value of the outcome measure when pushing with two hands of a total cart weight of 0 kg at hip height. Regression coefficients B5 – B10 of the two-way interaction terms were also calculated in the analyses but, for the sake of clarity, not visualized in the equation. As the independent variables can not be seen independent of each other in practice, all four dependent variables were forced into the model. Each of the interaction terms was screened separately for significance. Only significant interaction terms were added to the model. If multiple significant interaction terms had to be incorporated into model, only those that remained significant were added. A significance level of 5% was used. A goodness of fit at group level was achieved by comparing the group mean of the different combinations of the dependent variables to the values predicted by the GEE model. A linear regression analysis with an intercept forced through zero was used to calculate the proportion of the variance explained by the GEE model at group level.

The relationship between exerted push and pull forces and mechanical loading at the low back and shoulders was examined using Pearson correlation coefficients. For each participant the Pearson correlation coefficient was calculated separately and the mean correlation coefficient and standard deviation were determined.

3. Results

3.1. *Maximum values*

Table 2 presents the estimated regression coefficients for the maximum values found during the entire trial. To explain the results presented in this table, and tables 3 and 4, the results of the maximum value of the compressive force at L5-S1 will be discussed in more detail. The predicted constant value of 1521 N represents two handed pushing at hip height of a cart with a total weight of 0 kg. If the effect of pulling is compared to pushing the coefficient B1 of the main effect as well as the interaction coefficient B5 have to be taken into account. Pulling with two hands compared to pushing with two hands resulted in an increase in the predicted maximum compressive force of 763 N. However, pulling with only one hand was estimated to result in the about the same maximum compressive force as pushing with one hand. The main effect of using one or two hands was not significant. Therefore, the differences between using one or two hands depends on the interaction with pushing or pulling. When pushing, there were no significant differences between using one or two hands. When pulling, the decrease in the predicted maximum compressive force when using one instead of two hands would, therefore, be equal to the interaction coefficient B5 (774 N).

The effects of cart weight and handle height were also dependent on the interaction between cart weight and handle height. For pushing or pulling at hip height, the predicted maximum compressive force increased with 5 N for every kilogram that was added to the weight of the cart. At shoulder height the maximum compressive force would increase with a predicted value of only 2 N for every kilogram. With respect to the 320 kg cart used in the present study, at hip height the maximum compressive force at the low back would increase with 1600 N, while at shoulder height the maximum compressive force would increase only 640 N. As the main effect of handle height was not significant, the difference in maximum compressive force between hip and shoulder height depended on the weight that was pushed or pulled. The compressive force at shoulder height would be lower than at hip height by 3 N for every kilogram that is added to the weight of the cart. That is, for the 320 kg cart pushing or pulling at shoulder height would result in a decrease of 960 N compared to pushing or pulling at hip height.

All possible combinations of the factors and their predicted maximum compressive forces at the low back are presented in figure 1. Pushing an 85 kg cart with two hands at shoulder height resulted in the lowest predicted maximum compressive forces of almost 1500 N. The highest predicted value of nearly 4000 N was found for pulling a 320 kg cart with two hands at hip height. Figure 2 presents the group mean values of the actual measurements. A linear regression analysis to compare predicted and actual values at group level showed that 93% of the variance was accounted for (table 2).

Table 2. Results of GEE analyses to quantify the effect of pushing or pulling, using one or two hands, cart weight, and hip or shoulder height on *maximum values* of exerted forces and mechanical loading on the low back and shoulders. The actual values, standard errors (SE), and corresponding *p*-values are presented of the constant and the regression coefficients B1 – B10. The constant represents the predicted value of the outcome measures for two handed pushing of a 0 kg cart at hip height. The proportion of the explained variance (R^2) to compare the values predicted by the GEE model and the actual values at group level is presented.

Maximum value		Constant	1 Pushing (0) or pulling (1) B1	2 Two handed (0) or one handed (1) B2	3 Cart weight (kg) B3	4 Hip height (0) or shoulder height (1) B4	1 × 2 B5	1 × 3 B6	1 × 4 B7	2 × 3 B8	2 × 4 B9	3 × 4 B10	R^2
Resultant exerted force (N)	Coefficient	74.20	43.30	− 20.98	0.94	2.50			− 30.08				0.98
	SE	13.31	11.90	2.99	0.07	9.33			14.16				
	p-value	0.00	0.00	0.00	0.00	0.79			0.03				
Low back moment (Nm)	Coefficient	59.90	47.02	2.97	0.22	− 21.53	− 35.53						0.95
	SE	7.32	12.13	2.30	0.02	6.04	5.42						
	p-value	0.00	0.00	0.20	0.00	0.00	0.00						
Compressive force at L5-S1 (N)	Coefficient	1521.12	763.29	225.56	5.00	− 259.52	− 774.26					− 3.05	0.93
	SE	173.08	193.17	148.43	0.61	224.01	156.86					0.77	
	p-value	0.00	0.00	0.13	0.00	0.25	0.00					0.00	
Shear force at L5-S1 (N)	Coefficient	− 485.14	87.70	− 49.24	− 0.66	225.73			− 220.40				0.62
	SE	65.59	84.37	20.68	0.21	21.79			60.89				
	p-value	0.00	0.30	0.02	0.00	0.00			0.00				
Shoulder moment (Nm)	Coefficient	38.07	− 11.86	21.76	0.11	− 15.02					− 7.34		0.84
	SE	5.30	3.23	3.53	0.02	4.50					3.36		
	p-value	0.00	0.00	0.00	0.00	0.00					0.03		

Table 3. Results of GEE analyses to quantify the effect of pushing or pulling, using one or two hands, cart weight, and hip or shoulder height on values of the mechanical loading on the low back and shoulders *at the instant of the initial exerted force*. The actual values, standard errors (SE), and corresponding *p*-values are presented of the constant and the regression coefficients B1 – B10. The constant represents the predicted value of the outcome measures for two handed pushing of a 0 kg cart at hip height. The proportion of the explained variance (R^2) to compare the values predicted by the GEE model and the actual values at group level is presented.

Initial value		Constant	1 Pushing (0) or pulling (1) B1	2 Two handed (0) or one handed (1) B2	3 Cart weight (kg) B3	4 Hip height (0) or shoulder height (1) B4	1 × 2 B5	1 × 3 B6	1 × 4 B7	2 × 3 B8	2 × 4 B9	3 × 4 B10	R^2
Resultant exerted force (N)	Coefficient	73.09	44.95	– 22.26	0.94	3.48			– 32.98				0.98
	SE	12.68	13.31	3.65	0.07	9.33			14.94				
	p-value	0.00	0.00	0.00	0.00	0.71			0.03				
Low back moment (Nm)	Coefficient	38.52	50.92	9.45	0.13	– 26.25	– 35.19	0.12					0.95
	SE	5.50	10.28	3.51	0.02	5.40	6.28	0.05					
	p-value	0.00	0.00	0.01	0.00	0.00	0.00	0.01					
Compressive force at L5-S1 (N)	Coefficient	976.03	789.67	313.17	3.74	– 723.40	– 818.58						0.91
	SE	149.65	194.30	127.95	0.37	127.64	164.38						
	p-value	0.00	0.00	0.01	0.00	0.00	0.00						
Shear force at L5-S1 (N)	Coefficient	– 230.60	69.01	– 61.49	– 0.47	227.52			– 274.74				0.78
	SE	89.47	74.79	25.48	0.11	58.57			46.59				
	p-value	0.01	0.36	0.02	0.00	0.00			0.00				
Shoulder moment (Nm)	Coefficient	32.78	– 20.47	23.37	0.16	– 4.54			18.75		– 12.88	– 0.10	0.93
	SE	5.48	7.30	2.99	0.01	4.75			7.39		2.75	0.02	
	p-value	0.00	0.01	0.00	0.00	0.34			0.01		0.00	0.00	
Compressive force at GH joint (N)	Coefficient	1014.76	– 668.72	230.75	4.48	– 4.29			657.12			– 2.16	0.66
	SE	116.56	34.14	104.89	0.30	183.13			210.06			0.96	
	p-value	0.00	0.00	0.03	0.00	0.98			0.00			0.03	

Table 4. Results of GEE analyses to quantify the effect of pushing or pulling, using one or two hands, cart weight, and hip or shoulder height on values of exerted forces and mechanical loading on the low back and shoulders *during the sustained phase of the pushing and pulling activities*. The actual values, standard errors (SE), and corresponding *p*-values are presented for the constant and the regression coefficients B1 – B10. The constant represents the actual value of the outcome measures for two handed pushing of a 0 kg cart at hip height. The proportion of the explained variance (R^2) to compare the values predicted by the GEE model and the actual values at group level is presented.

Sustained value		Constant	1 Pushing (0) or pulling (1) B1	2 Two handed (0) or one handed (1) B2	3 Cart weight (kg) B3	4 Hip height (0) or shoulder height (1) B4	1 × 2 B5	1 × 3 B6	1 × 4 B7	2 × 3 B8	2 × 4 B9	3 × 4 B10	R^2
Resultant exerted force (N)	Coefficient	23.24	−8.17	3.08	0.23	−2.29					−10.35	0.08	0.97
	SE	4.07	5.32	4.38	0.02	5.29					4.77	0.04	
	p-value	0.00	0.13	0.48	0.00	0.67					0.03	0.03	
Low back moment (Nm)	Coefficient	52.40	0.05	−9.06	0.07	−24.53					12.44		0.90
	SE	5.52	4.97	4.54	0.01	4.37					3.75		
	p-value	0.00	0.99	0.05	0.00	0.00					0.00		
Compressive force at L5 – S1 (N)	Coefficient	1081.58	255.28	93.01	2.03	−310.62	−260.03					−0.87	0.96
	SE	97.93	101.81	77.50	0.32	93.72	87.19					0.38	
	p-value	0.00	0.01	0.23	0.00	0.00	0.00					0.02	
Shear force at L5 – S1 (N)	Coefficient	−184.40	23.02	−34.01	−0.22	77.65			−65.30				0.61
	SE	31.41	35.29	22.07	0.10	26.92			18.77				
	p-value	0.00	0.51	0.12	0.03	0.00			0.00				
Shoulder moment (Nm)	Coefficient	10.27	−6.34	8.25	0.05	−1.83					−4.27		0.96
	SE	3.01	3.45	1.95	0.01	1.93					2.01		
	p-value	0.00	0.07	0.00	0.00	0.34					0.03		
Compressive force at GH joint (N)	Coefficient	470.53	−296.74	272.04	0.34	−17.00					−179.76	1.03	0.86
	SE	72.76	89.02	18.57	0.12	63.11					44.54	0.34	
	p-value	0.00	0.00	0.00	0.01	0.79					0.00	0.00	

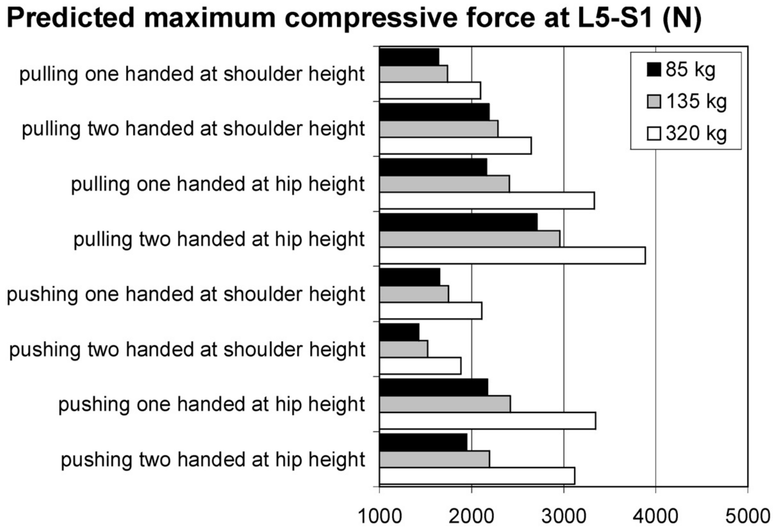

Figure 1. Quantification of all possible combinations of pushing and pulling, one and two handed, cart weight, and handle height in terms of predicted maximum compressive force at the low back. Results are estimated using GEE analyses.

For the remaining maximum values, all factors except handle height significantly affected the maximum resultant exerted force (table 2). Differences between pushing and pulling were found to be dependent on handle height, and the other way around. Except for the use of one or two hands, all factors significantly affected the maximum net moment at the low back. However, the interaction between pushing or pulling and the number of hands used appeared to be significant. One handed pulling was predicted to result in a significantly lower maximum low back moment (36 Nm) when compared to the other combinations of pushing, pulling, and number of hands used. Quantitatively, pushing or pulling and cart weight had a considerable effect on the maximum net moment at the low back. For displacing 320 kg, the maximum net moment would increase with 70 Nm. Except for the difference between pushing or pulling, which was dependent on handle height, all factors significantly influenced the maximum shear forces at the low back. Furthermore, all factors significantly affected the maximum value of the net moment at the shoulder.

3.2. *Initial values*

At the instant of the initial exerted force, all factors except handle height influenced the exerted force significantly (table 3). All factors also significantly affected both the net moment and the compressive force at the low back, including a significant interaction between pushing or pulling and the use of one or two hands. For the net moment also an interaction between pushing or pulling and cart weight was observed. Differences between pushing and pulling in initial shear forces at the low back were dependent on handle height. All other factors had a significant main effect. Pushing or pulling, the use of one or two hands, and cart weight significantly affected the net moment and compressive forces at the shoulder joint. Differences between handle heights were affected by pushing or pulling and cart weight and, for the net moment, also by the use of one or two hands.

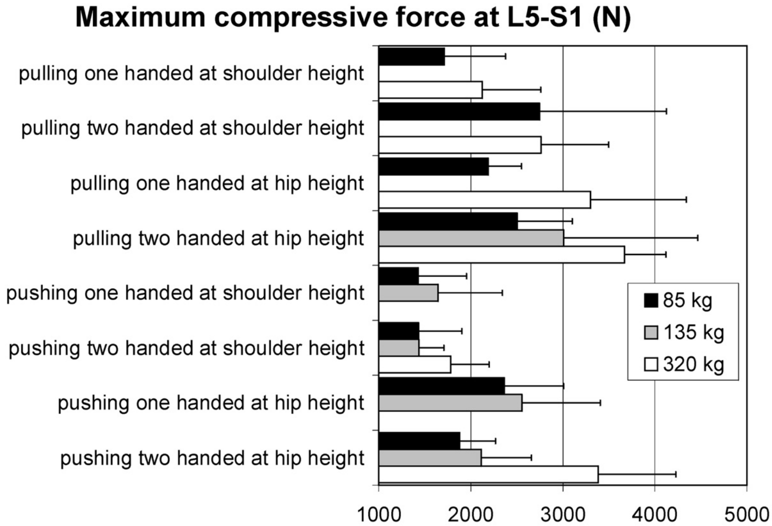

Figure 2. Participants' (n = 7) means and standard deviations of the actual values of the measured combinations of pushing and pulling, one and two handed, cart weight, and handle height in terms of maximum compressive force at the low back.

3.3. *Sustained values*

For the sustained values of the exerted forces only the main effect of cart weight was significant (table 4). Interactions of handle height with both the use of one or two hands and cart weight were observed. All factors except pushing or pulling had a significant effect on the sustained net moment at the low back. The compressive force at the low back was significantly affected by all factors except the use of one or two hands, which appeared to be dependent on pushing or pulling. The main effects of cart weight and handle height for the shear forces at the low back were significant. Differences between pushing and pulling were dependent on handle height. Pushing or pulling did not significantly affect the shoulder moment. Differences in shoulder moment between hip and shoulder height were dependent on the use of one or two hands. The compressive forces at the shoulder were significantly affected by all factors except handle height, which was dependent on both the use of one or two hands and cart weight.

3.4. *Relationship between exerted forces and mechanical load*

Table 5 presents Pearson correlations to describe the relationship between the exerted forces and the mechanical load on the low back and shoulder, averaged over participants. Initial and maximum exerted forces had a correlation coefficient of 1.00 (SD 0.00), which means that initial exerted forces were the highest exerted forces during the pushing and pulling tasks. Moderate correlations were observed between the maximum and initial exerted forces and the maximum and initial net moments at the low back, ranging between 0.56 and 0.69. However, correlations between the exerted forces and the compressive and shear forces at the low back and the net moments and compressive forces at the shoulder were lower, ranging between -0.30 and 0.54.

Table 5. Participants' ($n = 7$) means and standard deviations of Pearson correlations to describe the relation between the exerted forces and the mechanical load on the low back and shoulder. Correlations are calculated for the maximum values and for the initial and sustained phases.

	Maximum resultant exerted force (N)	Initial resultant exerted force (N)
Maximum values		
Resultant exerted force (N)	–	1.00 (0.00)
Low back moment (Nm)	0.69 (0.09)	0.68 (0.08)
Compressive force at L5-S1 (N)	0.46 (0.18)	0.46 (0.18)
Shear force at L5-S1 (N)	− 0.30 (0.22)	− 0.29 (0.22)
Shoulder moment (Nm)	0.34 (0.19)	0.33 (0.18)
Compressive force at GH joint (N)	–	–
Initial values		
Resultant exerted force (N)	1.00 (0.00)	–
Low back moment (Nm)	0.57 (0.13)	0.56 (0.14)
Compressive force at L5-S1 (N)	0.53 (0.14)	0.53 (0.14)
Shear force at L5-S1 (N)	− 0.23 (0.29)	− 0.22 (0.30)
Shoulder moment (Nm)	0.33 (0.15)	0.32 (0.14)
Compressive force at GH joint (N)	0.51 (0.30)	0.50 (0.31)
Sustained values	Sustained resultant exerted force (N)	
Resultant exerted force (N)	–	
Low back moment (Nm)	0.32 (0.27)	
Compressive force at L5-S1 (N)	0.31 (0.24)	
Shear force at L5-S1 (N)	− 0.17 (0.26)	
Shoulder moment (Nm)	0.54 (0.13)	
Compressive force at GH joint (N)	0.47 (0.52)	

4. Discussion

The main objective of the present study was to examine the effect of potential risk factors of pushing and pulling on the exerted forces and the mechanical load on the low back and shoulders. Results indicate that exerted forces, net moments, and compressive and shear forces are differently affected by pushing or pulling, the use of one or two hands, and handle height. Discrepancies exist between analyses at the level of exerted forces and net moments on the one hand and at the level of compressive and shear forces on the other hand. Only cart weight affected each of the dependent variables significantly, i.e., an increase in cart weight resulted in a significant increase of all dependent variables. Although initial exerted forces were relatively highly correlated with the maximum and initial low back moments, correlations with other measures of mechanical load at the low back and shoulder appeared to be low.

4.1. *Application of methods*

In the present study, a three-dimensional EMG driven biomechanical model was used to estimate compressive and shear forces. Marras (2000) states that three-dimensional EMG driven models are the most accurate biomechanical models available at the moment to estimate low back loading. However, the validation of these types of models is very difficult to study and should, therefore, not considered to be sufficient. Furthermore, the application of the present model may have resulted in somewhat overestimated values of compressive and shear forces. The lever arm of the extensor muscles was found to be relatively small, probably because the anatomical data of the model represent those of a smaller than mean male (Van Dieën and De Looze 1999). Generally, the predicted maximum compressive forces were below the recommended NIOSH limit of 3400 N (NIOSH 1981). Predicted maximum shear forces were below 800 N. However, tolerance limits for shear forces are not sufficiently known and there is much diversity of opinion (Lamy *et al.* 1975, McGill 1997). Furthermore, the geometry of the model causes the shear forces to be highly sensitive to changes in posture as well as measurement errors in posture (Van Dieën and De Looze 1999). Hence, the results with respect to shear forces should be approached cautiously.

A first attempt was made to distribute the net moment at the shoulder and estimate the compressive force at the glenohumeral joint during work-related pushing and pulling activities. So far, the ergonomics application of the present shoulder model had been limited to wheelchair propulsion and bricklaying (Visser *et al.* 1994, Van der Helm and Veeger 1996). The shoulder model is able to estimate, among others, muscle lengths, muscle forces, and compressive forces in several joints. In the present study the compressive force at the glenohumeral joint was chosen to represent the internal mechanical load at the shoulder. Although an epidemiological association between the compressive force and shoulder complaints has not been studied yet, it is assumed that the compressive force can be considered a suitable measure because it reflects all forces that are acting on the glenohumeral joint (Praagman *et al.* 2000). Also, compressive forces are largely determined by the rotator cuff muscles that compensate for the shear forces on the glenohumeral joint. These (upward directed) shear forces, when insufficiently compensated, are thought to be the cause of impingement.

GEE was used to quantify the effect of the potential risk factors of pushing and pulling. GEE is mostly used for longitudinal epidemiological analyses (Twisk 1997). The application in the present study is justified by the fact that results within participants can be assumed to be repeated measurements and are therefore not independent. Application of regular linear regression analyses would presumably result in more or less comparable regression coefficients, but confidence intervals are expected to be too small. Linear regression analyses to compare the group mean values and the values predicted by the GEE model showed that more than 90% of the variance was always accounted for, except for shear forces at the low back and compressive forces at the glenohumeral joint (61–84%).

4.2. *Mechanical load at the low back*

An increase of the net moment at the low back as a result of pulling compared to pushing and a higher cart weight, and a decrease of the net moment as a result of a higher handle height are for the greater part confirmed by several studies (Abel and Frank 1991, Van der Woude *et al.* 1995, De Looze *et al.* 2000a). However, De Looze *et al.* (2000a) reported significant differences in net moment between pushing and pulling also during the sustained phase. These results could not be confirmed by the present study. The most likely explanation for this contradiction is the use of different types of carts. To the authors' knowledge the effect of the use of one or two hands during pushing and pulling has not been specifically studied, mainly because two dimensional biomechanical models have been applied. However, Lavender *et al.* (1998) reported no differences in the sagittal flexion moment between two handed symmetrical and one handed asymmetrical maximal pulling tasks, which is in contrast to the findings of the present study.

Several studies have reported on compressive and shear forces during pushing and pulling activities (Ayoub and McDaniel 1974, Lee 1982, Chaffin *et al.* 1983, Lee *et al.* 1989, 1991, Andres and Chaffin 1991, Gagnon *et al.* 1992, Kumar 1994, Resnick and Chaffin 1995, Van der Woude *et al.* 1995, Straker *et al.* 1997, Lavender *et al.* 1998). Generally, these studies reported higher compressive forces during pulling compared to pushing, for which there are two explanations. Firstly, net moments at the low back were reported to be higher during pulling (De Looze *et al.* 2000a). Secondly, most studies assume a single equivalent muscle model where net moments are the result of the activity of one muscle, either one back muscle or one abdominal muscle. Therefore, pulling would result in higher compressive forces because the lever arm of the trunk flexors in these models is much larger than the lever arm of the trunk extensors (Kroemer 1974, Andres and Chaffin 1991, Lee *et al.* 1991, Gagnon *et al.* 1992). However, large contrasts are present between the aforementioned studies, and also in relation to the present study, with respect to the level of compressive forces reported. The distribution models used to estimate compressive forces may to a certain extent account for the differences. Several authors (Lee *et al.* 1989, Thelen *et al.* 1996, Lavender *et al.* 1998, Nussbaum *et al.* 1999) have reported on antagonistic co-contraction of trunk flexor and extensor muscles during pushing and pulling activities. In the present study, antagonistic muscle activity was also present, especially during pushing activities, although net moments appeared to be relatively low. Van Dieën and De Looze (1999) showed that compression and shear estimates were affected by co-activity. It is estimated that during pushing and pulling activities, compressive forces would increase with 10–15% as a consequence of accounting for co-contraction using the EMG driven model (unpublished data). Another explanation for differences in results between studies may lie in the task constraints. The dimensions of the carts used in relation to its position of the centre of mass could have limited the direction of the exerted forces, and, therefore, could have affected the mechanical load.

4.3. *Mechanical load at the shoulder joint*

Only few studies reported mechanical load on the shoulder joint during pushing and pulling, and only in terms of net moments (Abel and Frank 1991, Van der Woude *et al.* 1995, De Looze *et al.* 2000a). Handle height and the magnitude of the exerted force (note that required exerted forces are significantly related to cart weight) were found to be significantly related to the net moment at the shoulder. The general idea is that net moments at the shoulder are kept low during pushing and pulling activities by keeping the wrist, elbow, and shoulder close to the line of action of the exerted force or by directing the exerted force such that the shoulder joint remains close to the line of action of the exerted force (Hoozemans *et al.* 1998).

A relatively small increase in compressive force at the glenohumeral joint with an increase in cart weight during sustained pushing and pulling at hip height was observed, while at the instant of the initial force the increase was relatively large. Again, task constraints may have caused these differences. It may be hypothesized that the relatively high levels of exerted forces needed to accelerate the cart would have tilted the cart when forces were exerted in a favourable direction to maintain relatively low levels of mechanical load at the shoulder. Tilting of the cart was prevented by directing the exerted force in a less favourable directed which resulted in a relatively large increase in mechanical load at the shoulder with an increase in cart weight compared to the sustained phase.

4.4. *Relationship between exerted forces and mechanical load*

Initial exerted forces were found to be the highest exerted forces during the pushing and pulling activities. Furthermore, the initial exerted forces were relatively highly correlated with the maximum and initial low back net moments. However, for all other measures of mechanical load at the low back and shoulder, the correlations with the exerted forces were low. Therefore, the hypothesis that higher initial and sustained exerted forces are related to higher mechanical loading at the low back and shoulder could not be confirmed. This means that measuring initial and sustained exerted forces at the workplace is not indicative for the peak and sustained mechanical loading at the low back and shoulders. The most likely explanation is that the mechanical loading is determined for a larger part by factors other than the absolute magnitude of the exerted forces. Firstly, the direction of the exerted forces with respect to the joints also determines the mechanical loading and should be taken into account during the assessment at the workplace (Van der Beek *et al.* 1999, De Looze *et al.* 2000a). Secondly, it can be expected that posture and movement largely determine the mechanical load compared to the exerted forces. For lifting relatively light objects, the mechanical load at the low back is largely determined by the amount of bending of the trunk and to a lesser extent by the weight of the handled object (Van der Burg *et al.* 2000, De Looze *et al.* 2000b) However, it is expected that for exerted forces higher than the forces assessed in the present study, the relative contribution of the exerted forces to the mechanical load will increase.

4.5. *Ergonomics implications*

The regression coefficients and, therefore, the quantified effect of the potential risk factors on the mechanical load at the low back and shoulders are specific to the cart and surface used in the present study. As the experiments were standardized, it is possible to generalize the relative quantitative effects of changes within the risk factors to situations outside the laboratory. However, the absolute level of the exerted forces and mechanical load might be different for situations with different carts and surfaces. Recently, Al-Eisawi *et al.* (1999) reported on minimum exerted forces required to push or pull carts. The diameter of the wheels and the surface appeared to be important factors, next to the weight of the cart which is confirmed by the results of the present study. According to Al-Eisawi *et al.* (1999) the results of the present study can be generalized to using carts with hard rubber wheels on a tile or asphalt surface, which is commonly used in, for instance, distribution centres.

The quantification of the effect of the potential risk factors of pushing and pulling can be used to determine ergonomics implications. For instance, pulling an 85 kg cart at hip height would result in the same predicted maximum compressive force at the low back as pulling the 320 kg cart at shoulder height. Thus, while maintaining a certain level of mechanical load, a change in working technique might result in the necessity to diminish the weight of the cart or, when a more favourable working technique is used, in a possibility to increase the weight of the cart. It is possible to quantitatively compare different working situations and the process of arriving at an optimum ergonomics working situation can be monitored in advance.

4.6. *Conclusions and recommendations*

Several potential risk factors of pushing and pulling had a significant effect on the mechanical load at the low back and shoulders. Cart weight as well as handle height appeared to affect the mechanical load at the low back and shoulder considerably and it is recommended that low cart weights are maintained and carts are used and designed such that it is possible to push or pull at shoulder height. However, several interaction effects appeared to be present, which have to be considered in the ergonomics design. Finally, initial and sustained exerted forces appeared not to be indicative for the mechanical load at the low back and shoulders within the studied range of the exerted forces.

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